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## Abstract

Major issues at Tevatron injection are the effects of 72 long-range beam-beam interactions together with the machine nonlinearity on protons and anti-protons. We look at particle tracking calculations of Dynamic Aperture(DA) under present machine conditions. Comparisons of calculations with observations and experiments are also presented in this report.

## 1 INTRODUCTION

In Run IIa the Tevatron is operating with 36 proton and anti-proton ( $\bar{p}$ ) bunches, both are distributed in 3 trains of 12 bunches [1]. The Tevatron is initially filled with three trains of twelve proton bunches. The bunches are spaced 21 rf buckets apart. They are injected onto the central orbit and subsequently moved to a helical orbit before anti-protons are injected. The anti-protons are injected four bunches at a time into the abort gaps between the proton bunches, we call this stage Cog0. After the leading four bunches in each train is injected, the anti-protons are clogged by 84 rf buckets to make room for the next four bunches in the abort gap, we call this stage Cog1. The leading eight bunches in each train are clogged again by 84 buckets to allow the injection of the last four bunches in each train. After each train is full, which we call stage Cog2, the two beams are accelerated to top energy, the optic keep unchanged during the ramp. The main beam parameters of the machine conditions at injection are listed in Table 1

Table 1: Beam parameters at injection energy

Parameter	present ( $p/\bar{p}$ )	Design ( $p/\bar{p}$ )
Bunch intensity (E11)	2.2/0.13	2.7/0.3
Emittance (95 %) ( $\pi\text{mm}\cdot\text{mrad}$ )	25/20	20/15
Momentum spread (r.m.s., $\sigma_p$ )	$7. \times 10^{-4} / 4.5 \times 10^{-4}$	$4.3 \times 10^{-4} / 4.3 \times 10^{-4}$
Chromaticities	(8,8)	(8,8)
working point	(0.583,0.575)	(0.585,0.575)

## 2 DYNAMIC APERTURE OF PROTONS

One of the key observations at injection is that the lifetime of the protons drops substantially when they are

moved from the central orbit to the helical orbit. Fig. 1 shows the DAs(Dynamic Aperture,in unit of beam size  $\sigma$ ) of coalesced and uncoalesced protons on center orbit and on proton helix orbit. Particles are tracked for 100,000 turns (2 seconds in the Tevatron). Chromaticity and feed-down sextupoles and measured field errors of all the magnets in the ring were included in this calculation. It is evident that the nonlinearities have a major impact since the DA of uncoalesced protons( $dp/p < 1.E-4$ ) on central orbit and on helix is larger than  $6\sigma$ , while the DA of coalesced beam is about  $8\sigma$  on central orbit and about  $5\sigma$  on the helix. The physical aperture is (4 - 6  $\sigma$ ), limited at C0. In a typical store, we observed proton lifetime on the central orbit is 4-6 hrs, but 1.5-2 hrs on the helix.

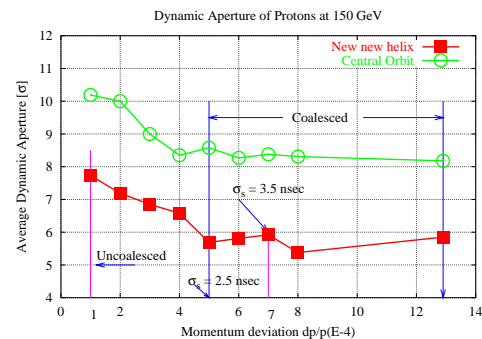


Figure 1: Dynamic aperture of protons.

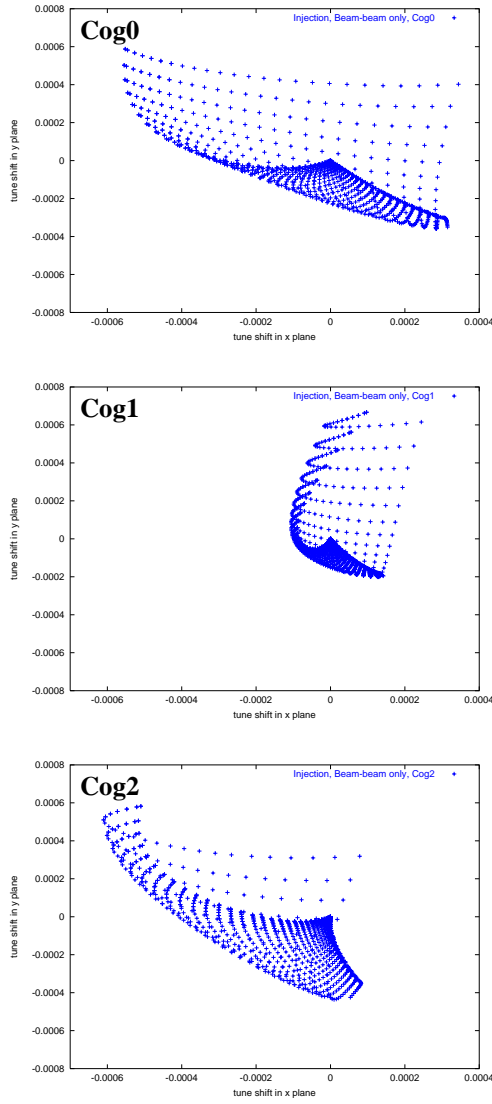
## 3 BEAM-BEAM EFFECTS ON ANTIPROTONS

Each anti-proton bunch experiences 72 long-range interactions during injection(after 2nd cogging). Totally there are 138 interaction points in the ring. Fig. 2 shows the separations of all 138 interaction points in the ring after 2nd cogging. The separation follows dispersion pattern since currently the momentum spread of the beam is large. The minimum separation is about  $3\sigma$ . Beam-beam effects are different for each anti-proton bunch in a train and at different cogging stages since the sequence of long-range interactions is different for each of them.

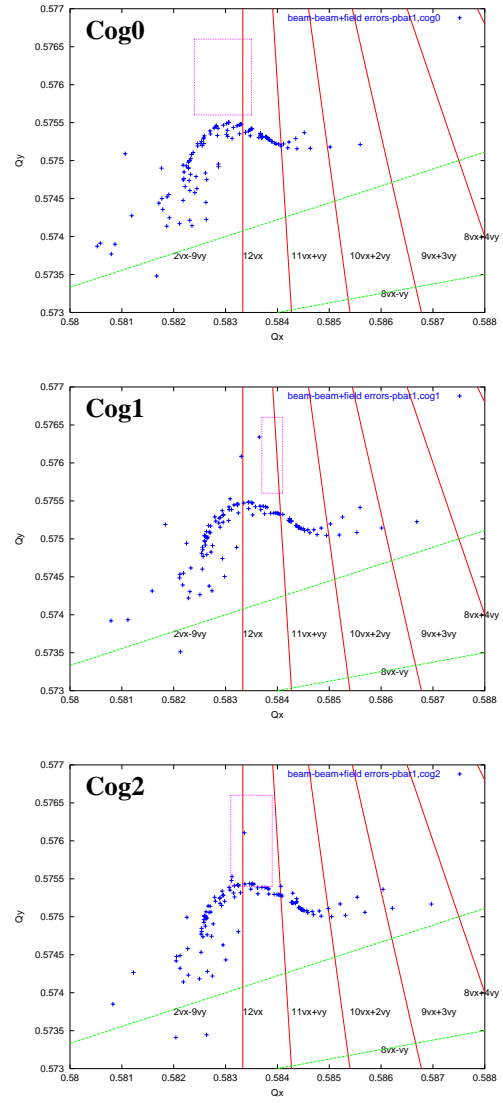
The left column of Fig. 3 shows the tune footprints of anti-proton bunch 1 with only beam-beam effects. Folds can be identified in these figures, at the folds resonance widths are large. When tune shift crosses zero, the beam-beam force has a maximum.

Long rang beam-beam force in the Tevatron creates an additional amplitude dependent chromaticities [2], the source of this chromaticity is the horizontal and vertical dispersion at the parasitic collisions which makes

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Only Beam-beam



Beam-beam and field errors

Figure 3: Footprint of  $\bar{P}$  bunch 1 at three cogging stages.

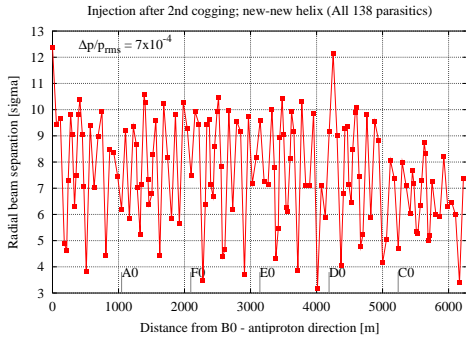


Figure 2: Radical beam separations at 138 interaction points in the ring.

the beam separation depend on the momentum deviation  $\delta p/p$ . Chromaticities due to beam-beam force can be calculated analytical for small amplitude particles. Fig. 4 gives the chromaticities of 12 anti-proton bunches in a train. This

additional chromaticities will enhance the synchro-betatron resonances. bunch to bunch difference can be identified too.

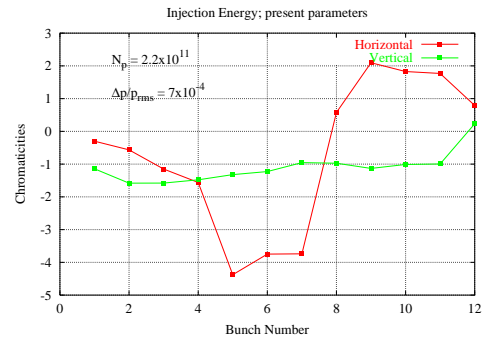


Figure 4: small amplitude beam-beam chromaticities at injection.

Beam-beam force also introduces additional coupling on

anti-protons. Coupling due to Beam-beam force can be calculated analytically. Like the tunes and the chromaticities, the strength of the coupling is an amplitude dependent quantity. Fig. 5 shows small amplitude beam-beam coupling for 12 anti-proton bunches in a train. Bunch to bunch difference in coupling can be identified.

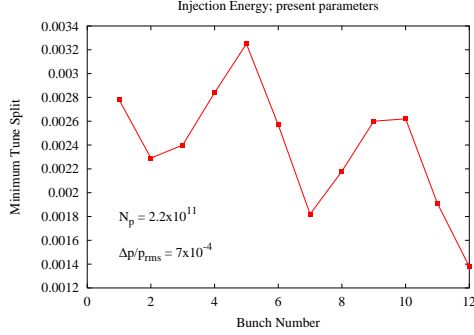


Figure 5: small amplitude beam-beam coupling at injection.

## 4 DYNAMIC APERTURE OF ANTI-PROTONS

Anti-proton's helical orbit is almost symmetric to the proton helical orbit. In addition to beam-beam effects from the protons, anti-protons are also subject to the machine nonlinearities. The right column of Fig. 3 gives the footprints of anti-protons at three cogging stages with beam-beam effects and field errors. The pink rectangular box in each plot indicates the range of the tune shift due to only beam-beam. Tune shifts of the particles due to field errors are much larger than those due to only beam-beam, footprints are dominated by field error. The footprints in three stages look similar.

The calculations of DA by tracking were done for anti-protons. It was found the average DAs are about  $4\sigma$ , and the same at three cogging stages. Fig. 6 gives DAs of  $\bar{p}$  in function of proton intensities at stage Cog2. It was also found that the DAs of  $\bar{p}$  are about  $2\sigma$  less than those of protons due to beam-beam effects. The difference between the bunches can be identified. DAs of the first and the last bunch in a train ( $\bar{p}1$  and  $\bar{p}12$ ) is better than those of the bunches in the middle of the train ( $\bar{p}6$  as a representative).

DA tracking at injection has received experimental confirmation. We extracted stores (10) with low anti-proton emittance lifetimes for the first 4 bunches (10 FW measurements in each store). From the asymptotic emittance, we calculated the DA. Fig. 7 shows the average DA from these stores for the 4 bunches. For one of the stores, we calculated the intensity reduction from assuming that the bunch occupies the final 3D DA. That agrees nicely with the observed intensity loss for all the 4 bunches.

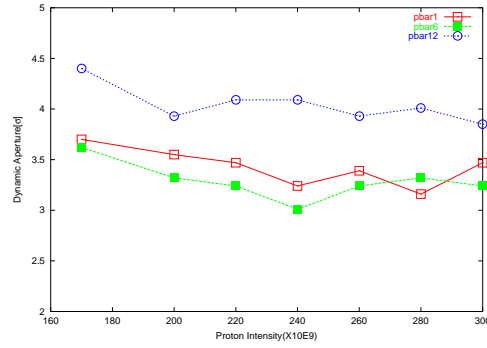


Figure 6: DA of  $\bar{p}$  vs. proton intensities at Cog2,  $10^5$  turns

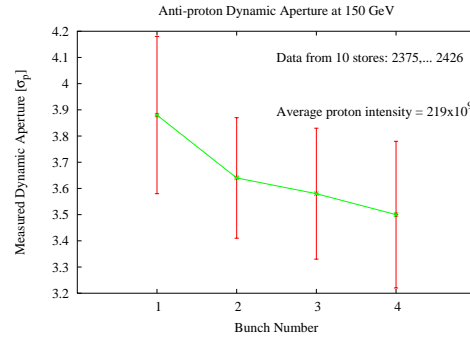


Figure 7: Measure Dynamic aperture at injection

## 5 CONCLUSION

At injection for uncoalesced beam, the DA of protons on the central orbit and proton helix is much larger than physical aperture at C0. For coalesced beam, the DA of protons on the helix is about  $6\sigma$  ( $\epsilon_x = \epsilon_y = 25\pi \text{ mm-mrad}$ ). Decreasing proton bunch length to design value (momentum deviation will be reduced from  $7.5 \times 10^{-4}$  to  $4.3 \times 10^{-4}$ ) would increase the lifetime significantly.

The average DA of anti-protons at injection is about  $4\sigma$ , and the minimum DA is about  $3\sigma$ , this value is the same at all 3 Cogging stages.

Anti-Proton lifetime at injection needs significantly improvement. It requires

- Change in the helical separations
- better control of machine nonlinearities (alignment)
- better working point
- smaller anti-proton emittance
- beam-beam compensation (under study)
- understanding of how lifetime scales with proton intensity

## 6 REFERENCES

- [1] [http://www-bd.fnal.gov/lug/runII\\_handbook/RunII\\_index.html](http://www-bd.fnal.gov/lug/runII_handbook/RunII_index.html)
- [2] Y. Alexahin, <http://www-ap.fnal.gov/meiqin/beam-beam01/beambeam01.html>.